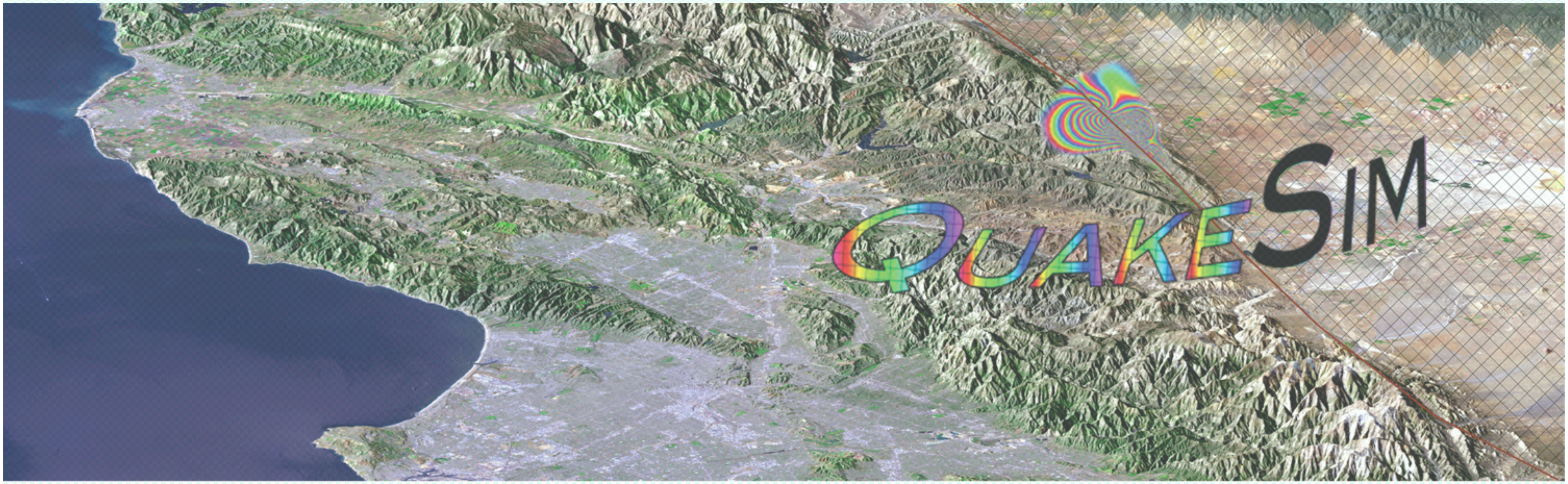
Application of GeoFEST with PYRAMID mesh refinement to Southern California crustal deformation



Jay Parker, Gregory Lyzenga, Margaret Glasscoe, Teresa Baker, Andrea Donnellan

Jet Propulsion Laboratory, California Institute of Technology

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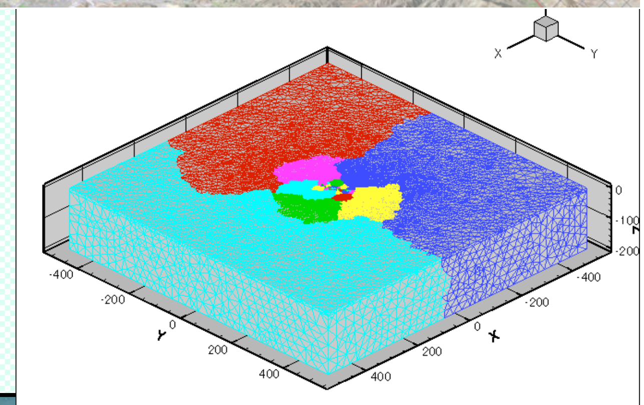
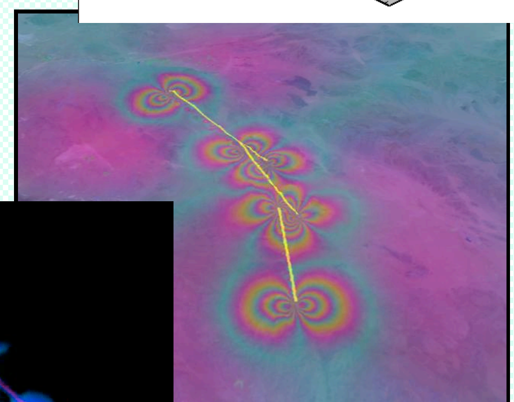
GeoFEST contributors

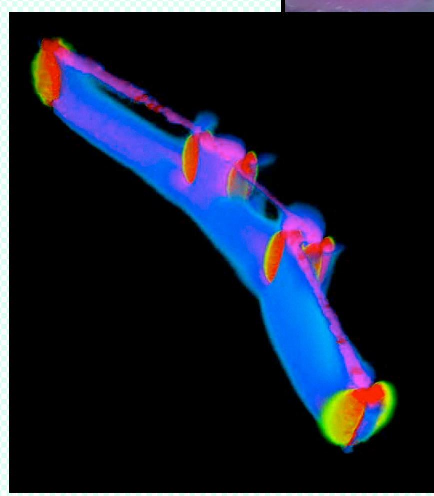
- Supported by the Computational Technologies Program of NASA's Earth Science Technology Office, http://ct-esto.jpl.nasa.gov/
- Project Principal Investigator -- *Andrea Donnellan*
- Management and Coordination -- *Michele Judd*
- guiVISCO object composer and mesher - *Jin-fa Lee (Ohio State)*
- PYRAMID, MPI Integration -- *Charles Norton, Edwin Tisdale*
- Validation -- *Cinzia Zuffada*
- Visualization -- *Peggy Li*
- Web Portal -- *Marlon Pierce (U. of Indiana)*

Why Mesh Refinement

- Why Stress/Strain, why Finite Elements
- Southern California settings, flexible meshing
- Parallel performance scaling for unstructured elements
- Cost of various mesh strategies
- Validation of fault stepover, refinement with strain energy







Why Stress/strain finite elements

•Earth Science is becoming pattern of *Monitor-Model-Assess-Predict*.

•New missions will generate 10 to 20 TB per week.

--Earth Science Enterprise Computational Technology Requirements Workshop, NASA, 2002

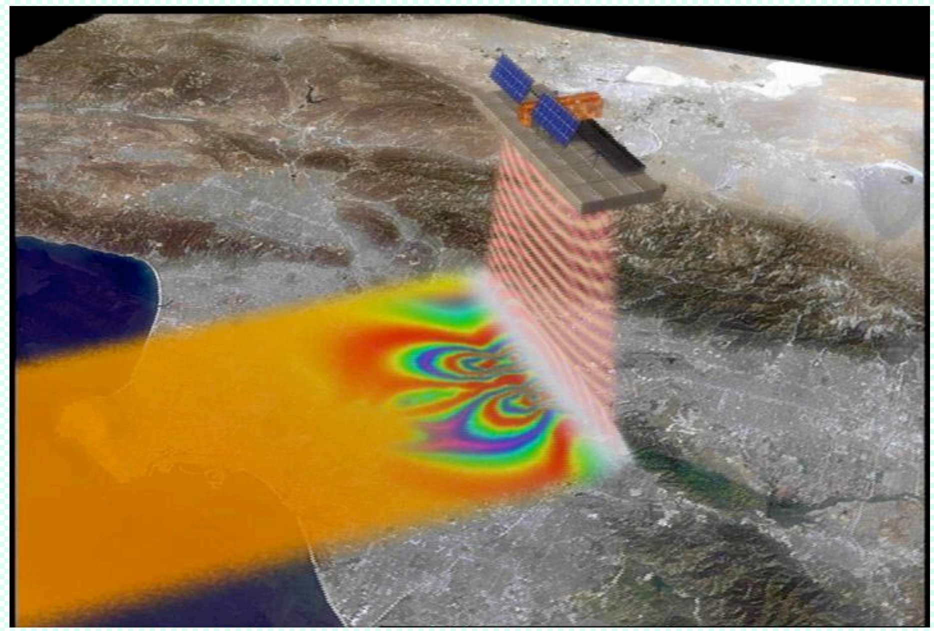
•Scales of earthquake sources span *eight* orders of magnitude (~fractal)

•Optimal use of data requires fit to a model

•Finite element mechanics fills key niche:

--couples to other methods (BE, . . .)

--approximate parameterizations (damage rheology, . . .)



Los Angeles Basin Compression

QuakeSim

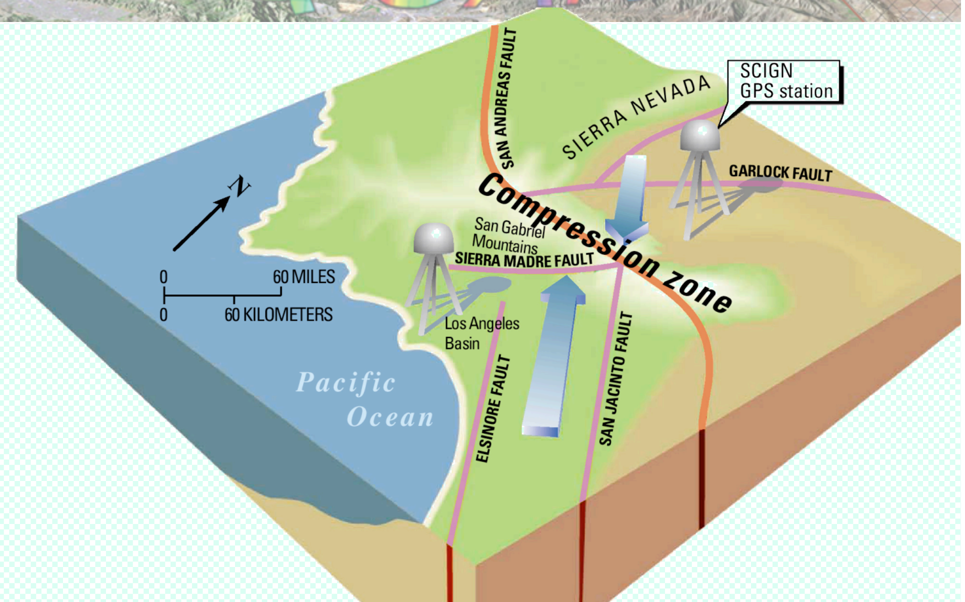
Demonstrate technology:

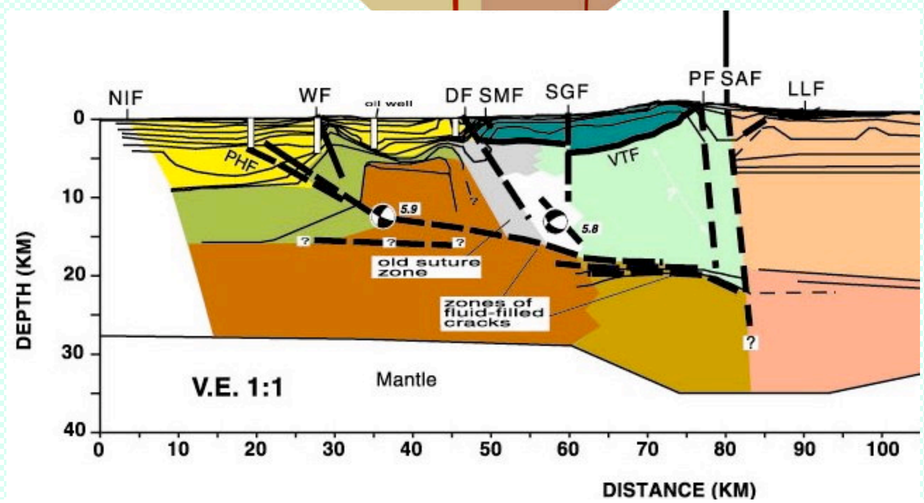
- Parallel AMR,
- >16 million finite elements,
- > 1000 time steps

Jointly match data:

- SCIGN velocity features
- Known fault rates
- Known mountain growth

--In progress.





Landers Event

Vertical Faults, Finite Element Nodes

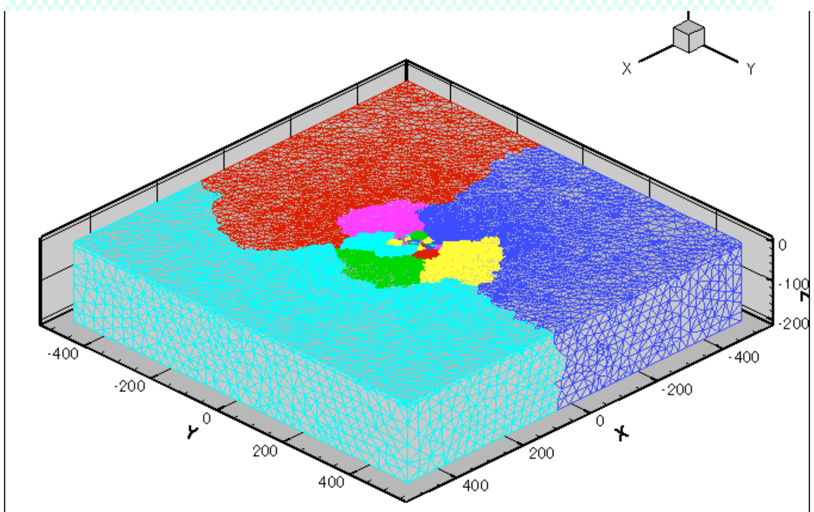
QuakeSim

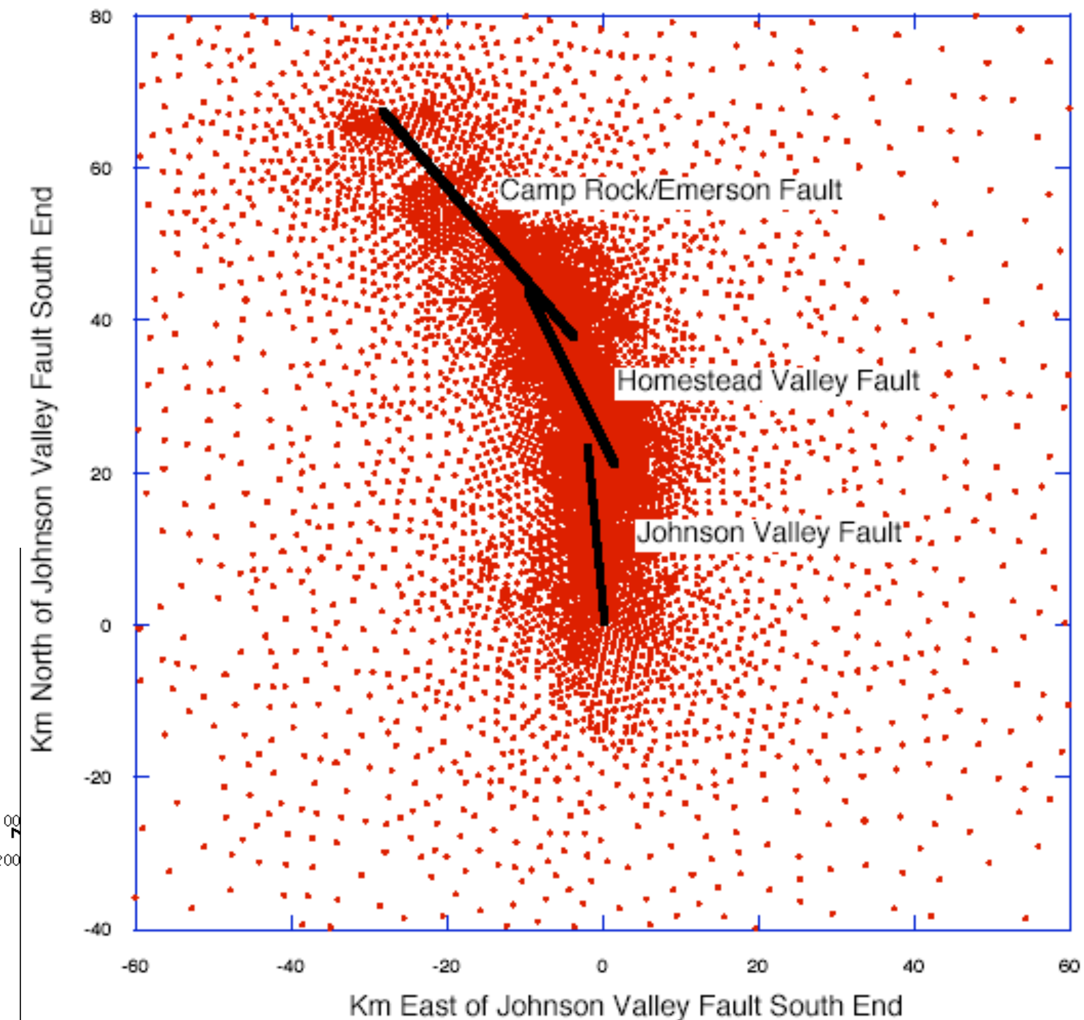
Demonstrate technology:

- Parallel AMR,
- >10 million finite elements,
- > 1000 time steps

Simulate event:

- Stress transfer
- Match GPS-observed regional relaxation





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What is GeoFEST?

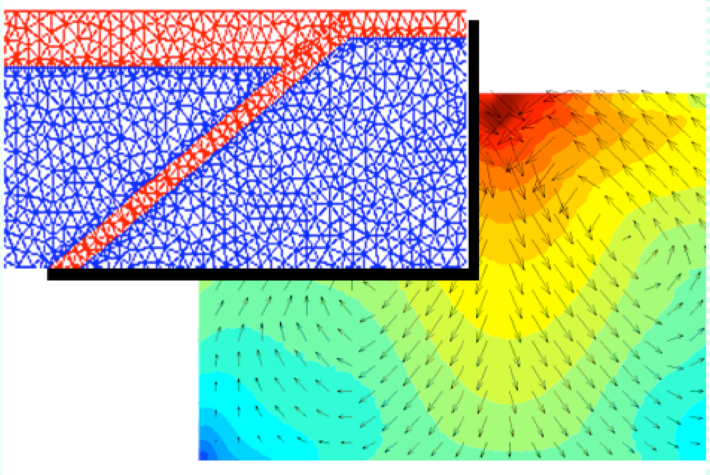
Geophysical Finite Element Simulation Tool

- Finite elements for elastic/viscoelastic stress, strain

- Unstructured 3-D meshes, material variations

- Fault dislocations and geophysical sources
    - —*stress-triggered fault slip*
    - —*non-Newtonian viscosity*
    - —*gravity, buoyancy*

- Support/development for
    - —*parallel computing*
    - —*adaptive mesh refinement*
    - —*visualization*
    - —*web computing*



GeoFEST Equations

Elastic equilibrium
$$\sigma_{ij,j} + f_i = 0,$$

Viscoelastic relaxation
$$\frac{\partial \sigma_{ij}}{\partial t} = c_{ijkl}\left(\frac{\varepsilon_{kl}}{\partial t} - \frac{\varepsilon_{kl}^{vp}}{\partial t}\right),$$

Isotropic material
$$c_{ijkl} = \mu(x)\left(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}\right) + \lambda(x)\delta_{ij}\delta_{kl},$$

Viscoplastic strain rate
$$\frac{\partial \varepsilon_{ij}^{vp}}{\partial t} = \beta_{ij}\left(\sigma_{ij}\right),$$

. . . so materials have lame parameters, viscosity, and body force

Two modes for using GeoFEST

QuakeSim Web Portal

+ Can do full projects in browser
+ No code port required
+ Runs remote jobs simply

— Under development

OpenChannel Download

+ GeoFEST, Pyramid full source
+ Can debug at any level
+ Runs on many platforms

— Compiler required

GeoFEST Problem Definition

Faults, Layers

Solid Geometry

Tetrahedral Mesh

Simulation Specification

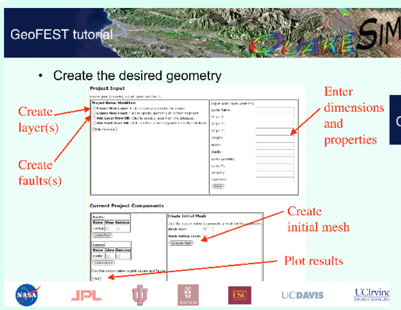
Material Properties

Boundary Conditions

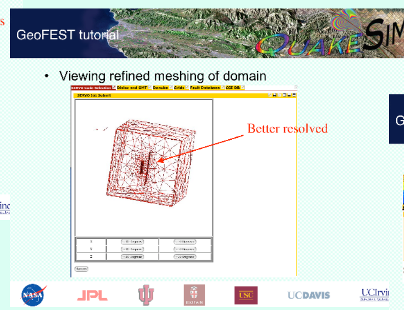
Input File

Run GeoFEST

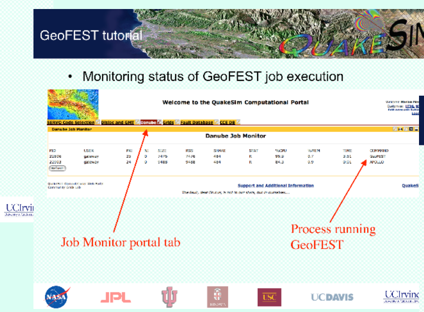
Visualization



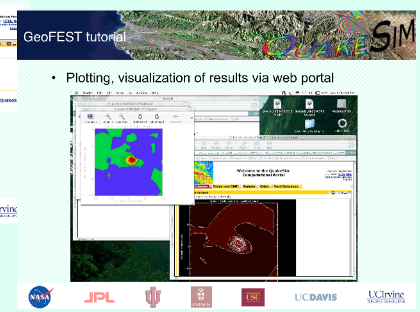
Setting geometry (QuakeTables fault database)



Mesh generation



GeoFEST simulation, job sumbission and control



Quick-view visualization

CT Project Milestones, Challenges

QUAKESIM

Baseline milestone (8/02):

- 50,000 elements, 1000 time steps
- Sequential execution in 13.8 hours

Parallel milestone (9/03):

- 1.25 million elements, 1000 time steps
- 64 processor Linux cluster in < 13.8 hours
  (attained 2.8 hours)

Final milestone (nominally 6/04):

- 16 million elements, 1000 time steps
- ~100's processor cluster in < 13.8 hours
- Demonstrate adaptive mesh refinement

The challenge: how costs scale

- File size: ~21 * Elements (compressed ASCII)
- Transfer time: ~3e-6 s * Elements (local network)
- Preprocessing: ~Elements
- Cluster memory: ~1e4 bytes*Elements
- Solve time: ~steps*(Elements)$^{4/3}$/Processors

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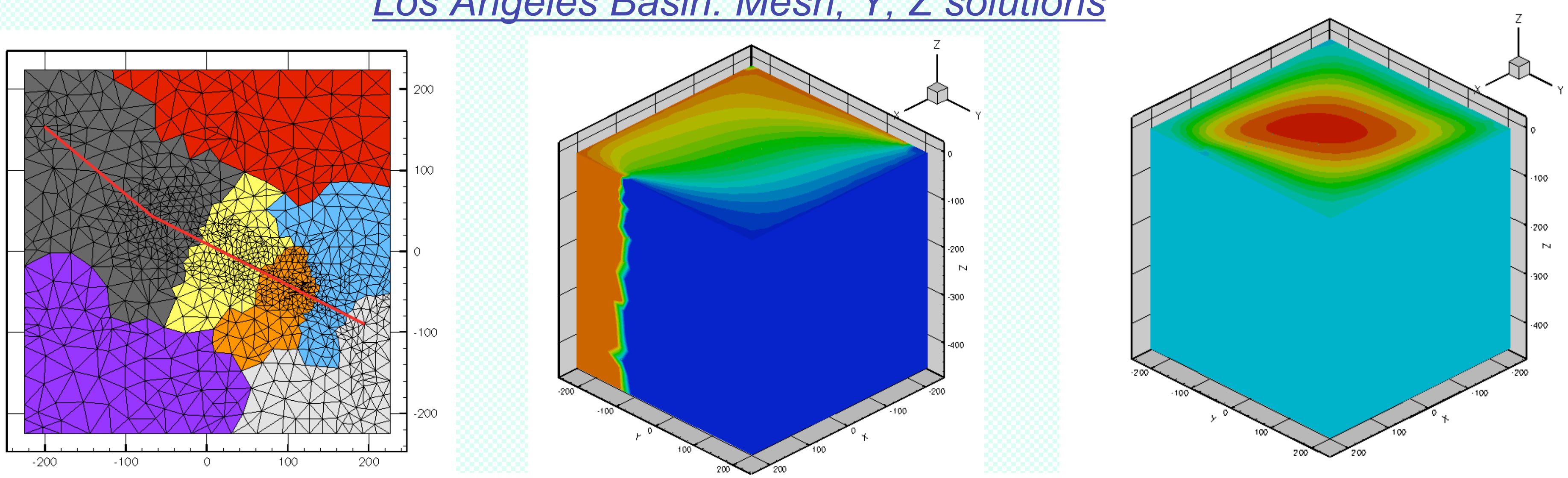
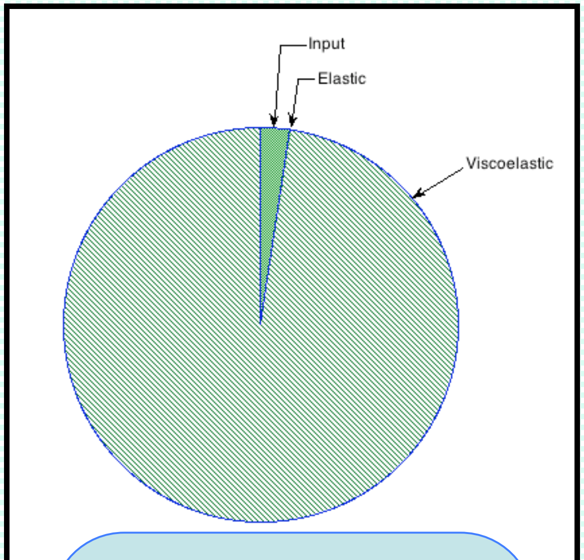
Pyramid Parallel Unstructured Adaptive Mesh Refinement Library

- A FORTRAN90-based software library
- For parallel unstructured adaptive mesh refinement
- Supports large-scale simulation applications with complex geometries.
- Manages partition of element domains on processors.
- With GeoFEST, solution-driven mesh improvement
- GeoFEST not using dynamic mesh modification

Los Angeles Basin: Mesh, Y, Z solutions



Parallel GeoFEST: Scaling

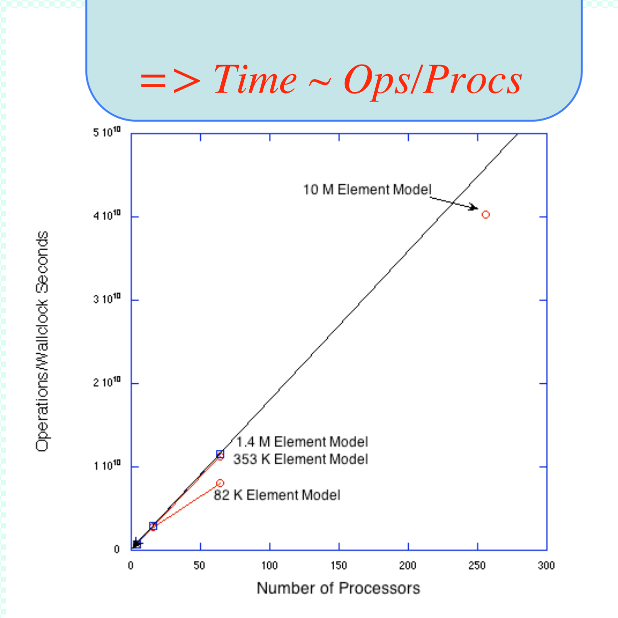


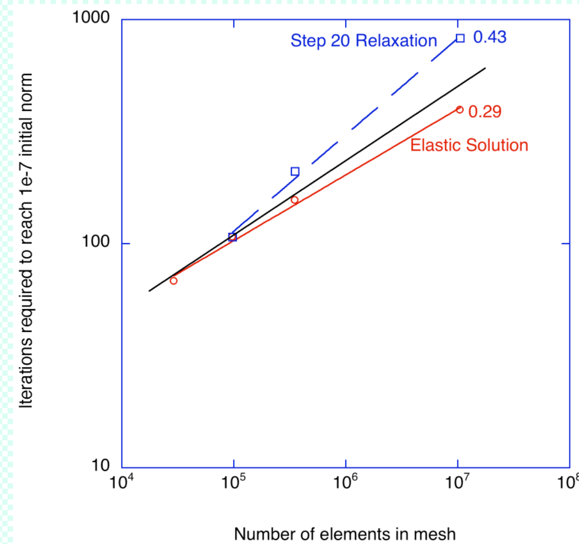
Landers, 1.4M elements
1000 time steps,
~200 iterations per step

=>Steps, iterations dominate time

Operations =
*Steps * Iterations * (~300)*Elements;*

=> Time ~ Ops/Procs



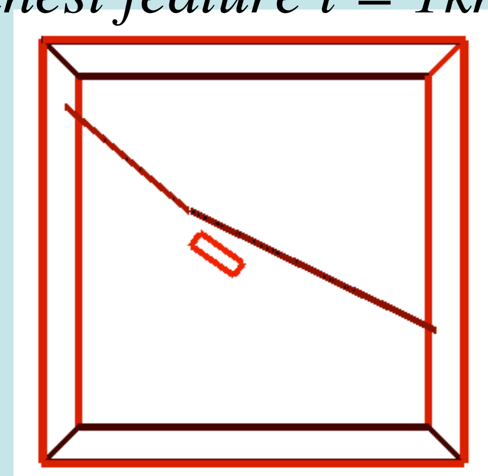


Iterations ~ Elements $^{(1/3)}$

=> Ops ~ Elts $^{(4/3)}$

How many elements?

Consider a L=500 (cube) domain, with a fault edge (finest feature l = 1km)



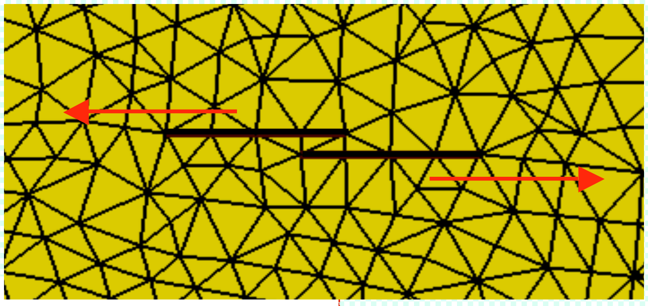
(motivated by LA Basin simulation geometry, shown here)

Some possible approaches:

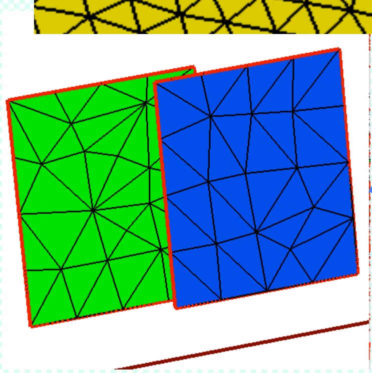
- **Fine** density mesh everywhere:
  Elements = $5(L/l)^3$ = 725M.
- **Heuristic** *(roughly what we use today):*
  --elements grow by "*A*" with distance from line.
  Nearest edge, need ~20*(L/l)
  Next, (to *A* km) another ~20*($L/(Al)$)
  to 2*A*, another ~20*($L/(2Al)$)
  . . . **Geometric progression**, so (optimistically)
  Elements ~$20(L/l)A/(A-1)$ ~ 30,000 (for A=1.5).
- Use **strain energy** from scratch solution to direct PAMR. Performance similar to heuristic, but *physics based*, *automatic*, *avoids errors*.

Adaptive Meshing (in progress)

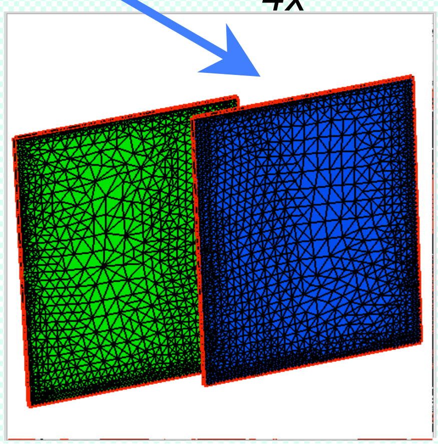
Initial surface mesh (center portion):



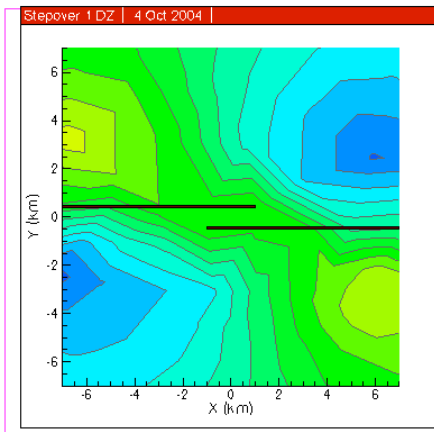
- Aim to use PYRAMID parallel library *(NASA ESTO CT Project)*
- Changes mesh after import to cluster
- Strain energy guides 3D refinement



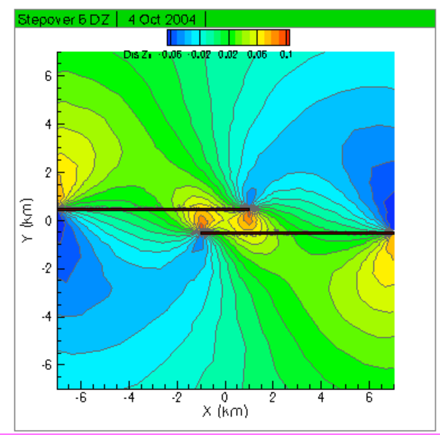
Obtain elastic solution
Strain energy
Refine
4x



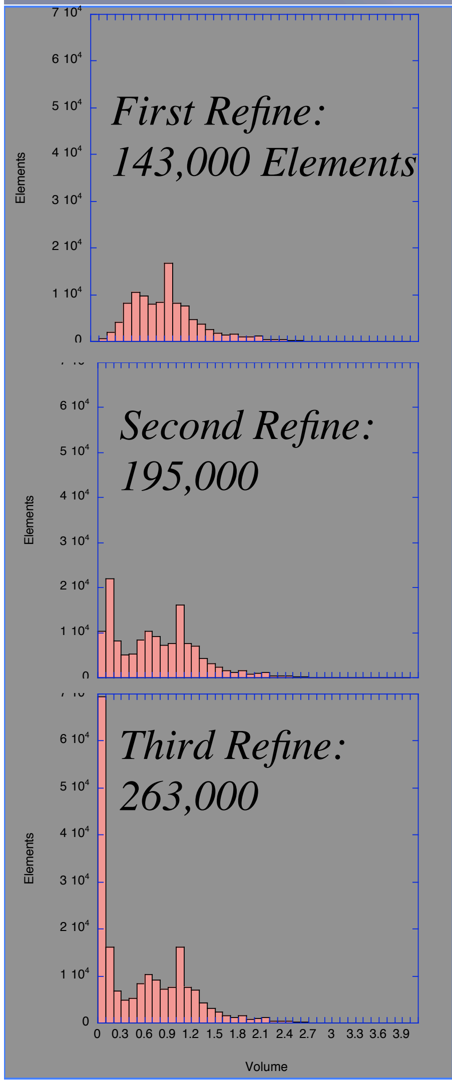
Mesh on faults (side view)



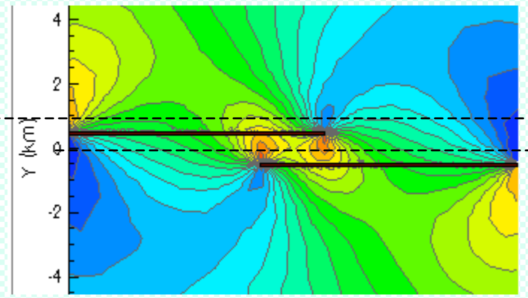
Z component at surface
Refinement cycles 1 and 6



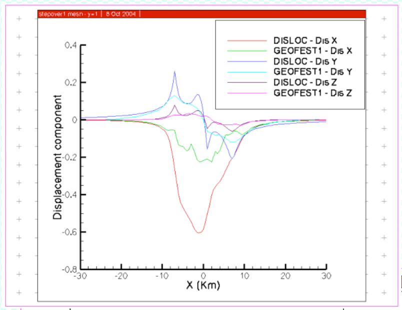
Detailed Validation
GeoFEST vs. Analytic Fault Stepover

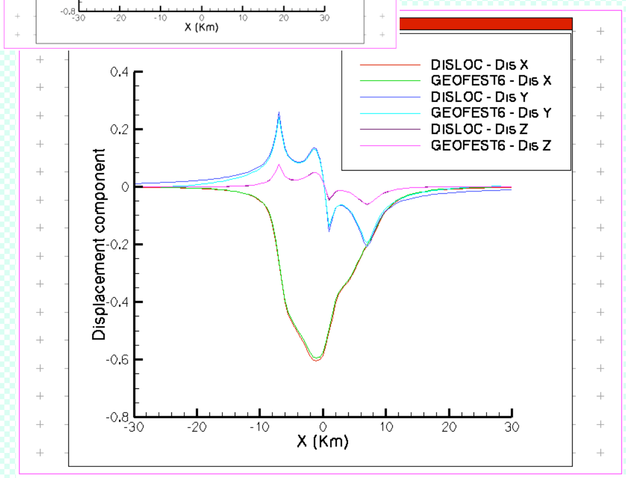


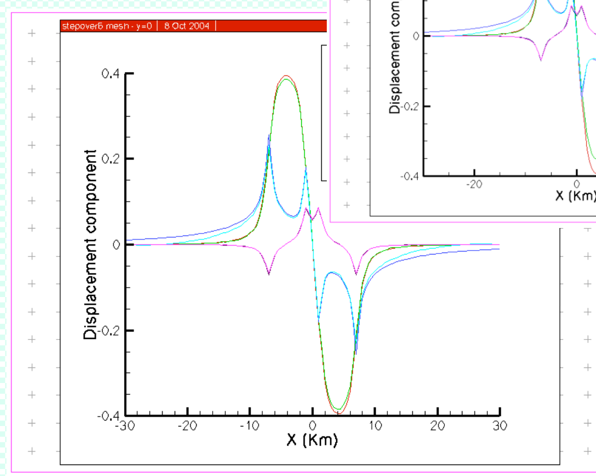
X,Y, Z components
Surface, horizontal line at y=1
Iteration 1 vs. 6

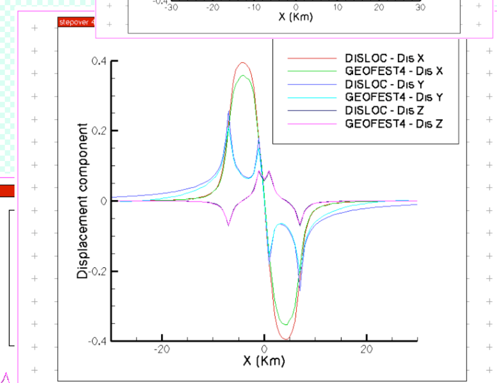


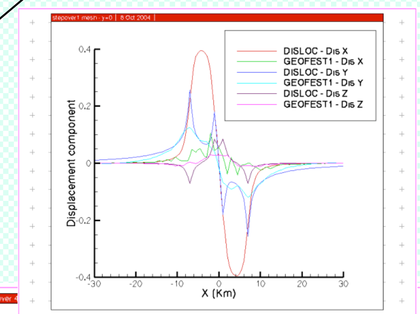
X,Y, Z components
Surface, horizontal line at y=0
Iterations1,4,6











GeoFEST Status

Summary

- Handles millions of elements in MPI code
- Heuristic mesher can vary density with high generality: High near fault edges, very low to extend to far boundaries
- PYRAMID integration works at first level (partition management) and generates quality refined meshes. Integration in progress.
- Strain Energy refinement converges to correct solution.
- Validation with known solutions indicates 1-2 iterations OK.
- Visit us at http://quakesim.jpl.nasa.gov

Background:
10M Element Landers coseismic uplift coded as radar phase,
256 Processors of SGI "Cosmos" system at JPL